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Development of an educational platform for vehicle-following control demonstration

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Abstract. *This paper presents the development of a testing platform for experimental demonstration of the vehicle-following task in an introductory control course. This platform is composed by one treadmill and up to two vehicles based on the combination of an Arduino board and a steerable scaled chassis. The vehicle is equipped with four DC motors and one step motor responsible for the four wheel drive and steering actuation, respectively. Three ultrasonic sensors monitor the following distance and the lateral displacement of the vehicle. Fundamental concepts of control design are addressed using this modern real-world implementation of vehicle automation to increase students interest and engagement. Topics such as system identification, closed-loop response and disturbance rejection are presented and discussed using the developed platform. An illustrative video of the demonstration is available at https://youtu.be/ss-UzZKDp_4. Arduino source code and additional Matlab scripts can be found at https://github.com/andresmendes/vehicle-prototype.*

Keywords: *Educational Platform, Control Education, Vehicle-following, Platooning, Arduino*

1. INTRODUCTION

Feedback control can be very challenging for students to learn, because of the required mathematical background and level of abstraction (Krauss, 2016). Experimental projects can help increase interest and engage students in class. Moreover, it promotes a better understanding of the content and develop the necessary skills for control engineers. For instance, *hands-on experience* using high-level systems and hardware is characterized as one of the most demanding skills in industry (Cook and Samad, 2009).

The introduction of experiments in a control class can be also challenging. One alternative are the commercially available control systems for educational purposes including hardware and software. However, those equipments can be very expensive reaching several thousand dollars. A low cost alternative is important to overcome the budget limitations on many universities. Moreover, inexpensive experiments can be used individually by the students and even used as take-home laboratories (Rossiter *et al.*, 2018).

One drawback of using micro-controllers is that students have to spend time in learning how to code the problem in a particular language. For introductory control course, this level of micro-controller programming could be excessive (Krauss, 2016). Besides, data acquisition for controller tuning and debugging can be facilitated using high-level programming such as Matlab or even block diagrams in Simulink.

Vehicle platooning is one control application with increasing interest from government, industry and academy (Mendes *et al.*, 2017). It consists of a set of vehicles following each other with small inter-vehicle distances. The main goal of this configuration is to reduce fuel consumption and greenhouse gas emissions while increasing the road capacity. As the vehicles travel closer to each other, a more efficient airflow is achieved reducing the overall energy consumption. The control problem of maintaining the platoon formation is vastly covered in the literature (Li *et al.*, 2017). However, the problem of vehicle-following control is rarely addressed in introductory control courses.

In order to increase interest and engagement of students, this paper presents a control platform representing a modern real-world application of vehicle-following control to illustrate fundamental concepts and design strategies in a introductory control course. The proposed platform should supplement the list of typical experiments used in control laboratory classes such as ball and plate, rotor dynamics, inverted pendulum or tank level control.

2. LITERATURE REVIEW

In engineering education, to overcome the cost limitations and go beyond simulation results, scaled prototypes are used to explore the fundamental aspects of a system. Related to vehicle control, for instance, Krauss (2016) presents a low cost autonomous vehicle platform based on the combination of Arduino and Raspberry Pi. This system has been used in a feedback control course and the effectiveness of the demonstrations was assessed using pre/post multiple choice quizzes. Alcantara *et al.* (2016) explore competency based learning in a vehicle dynamics course using a quarter car scaled platform. In both cases, the authors report a better learning outcome associated to control design and implementation after the introduction of the experiments.

Another vehicle platform is presented by Beal (2017) and used in an introductory engineering course. Students engaged in activities related to modeling and dynamic analysis, however, control strategies were not addressed. A 4WS/4WD vehicle platform is developed by Grepl *et al.* (2011) for research and education in mechatronics. The authors focused on estimation methods using several variants of Kalman filters and reported a successful use of the platform as an educational tool.

Exploring the vehicle-following task, Diab *et al.* (2010) present a scaled truck equipped with ultrasonic sensors, camera, WLAN modules and graphic user interface to investigate the effects of communication problems such as delays and loss of data on the platoon of trucks. The system architecture is complex and the cost of the equipment is significantly high. Therefore, the presented vehicle is not suited for an introductory control course. However, although the design of this vehicle is not intended for educational purposes, the detailed description of the project provide significant insight to the development of educational scaled platforms.

3. PLATFORM DESCRIPTION

The proposed vehicle is composed by one steerable plywood chassis, one Arduino MEGA, one motor shield, four DC motors, one step motor and three ultrasonic sensors. Figure 1 illustrates the vehicle components.

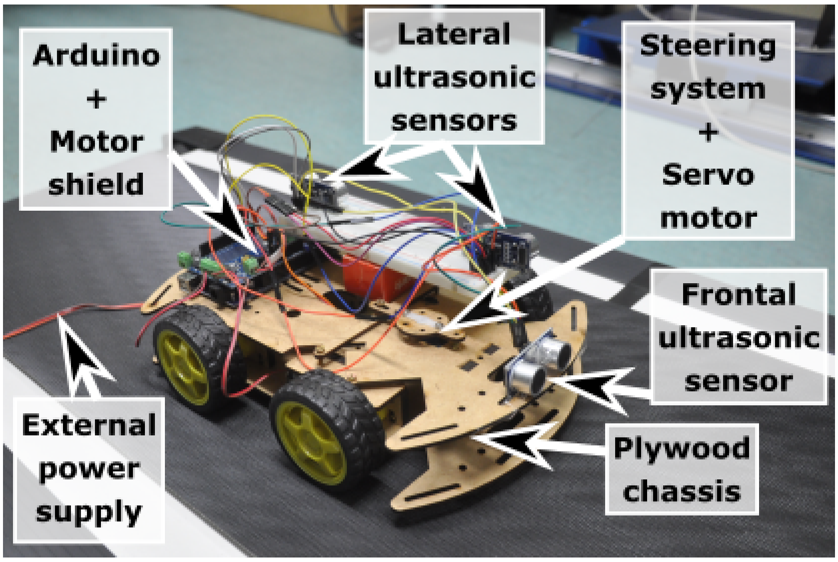

Figure 1. The main components of the scaled vehicle for platooning control demonstration.

One interesting feature of the chassis is the steering mechanism that allows orientation changes of the vehicle based on the front wheels steering. This mechanism is actuated through a step motor. The four DC motors provide a four wheel drive (4WD) capability to the prototype. One ultrasonic sensor in the front monitors the distance to the preceding vehicle. Two additional ultrasonic sensors are used to control the lateral position of the vehicle. The cost of each component can be found in Tab. 1. The total cost of the vehicle is approximately R$ 467.40 and the cost of the treadmill is R$ 867.75.

The full setup is shown in Fig. 2 with the vehicle on the treadmill. The longitudinal controller has to maintain a desired distance to the front end of the treadmill that represents the leading vehicle. Therefore, the first advantage of this platform setup is that only one vehicle is needed to test the vehicle-following controller. Different speeds of the conveying belt represent different speeds of a hypothetical leading vehicle. Another interesting feature of this configuration is the small space required for the experiment. Usually, tests of longitudinal vehicle controllers are performed on the floor requiring a lot of space to execute any maneuver. Besides, the conveying belt provide an uniform virtually endless surface for the test. This is also convenient for demonstrations, specially in classroom.

Table 1. Components of the scaled vehicle.

Component	Qty.	Unit price [R$]	Total price [R$]
Vehicle chassis	1	86.40	86.40
Arduino MEGA 2560 R3	1	94.90	94.90
Motor Shield Adafruit v2	1	176.90	176.90
DC motor 3-6V	4	13.90	55.60
Step motor 9g SG90	1	17.90	17.90
Ultrasonic HC-SR04	3	11.90	35.70
		Total	**467.40**

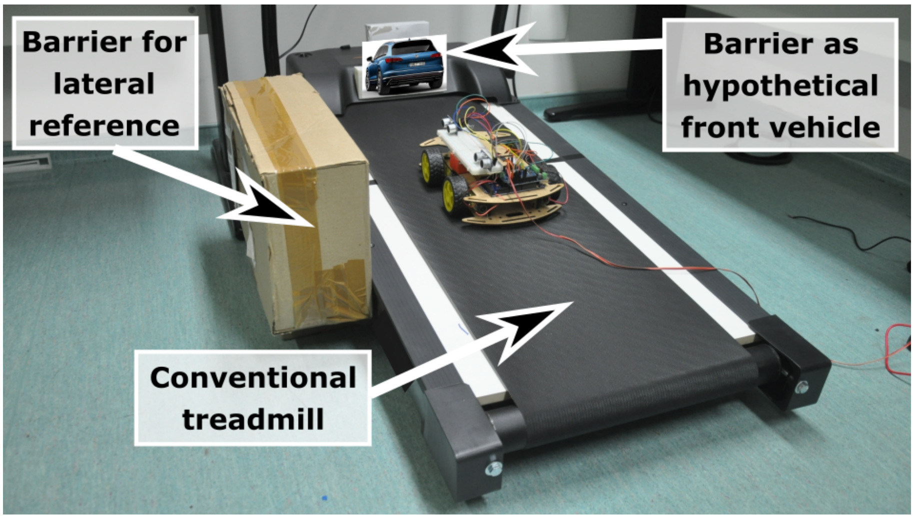

Figure 2. The scaled vehicle prototype on a conventional treadmill. The lateral barrier is used to keep the vehicle on track and the front barrier acts as a hypothetical front vehicle.

4. SYSTEM MODELING

The longitudinal dynamics of a conventional vehicle in a platoon is described by the differential equation

$$m_e\ddot{x} = F - mgc_r - mg\sin\theta(x) - \frac{1}{2}\rho A c_d \dot{x}^2 \Phi(d), \tag{1}$$

where x is the longitudinal position of the vehicle. The total mass is m and the effective mass is m_e accounting for rotational inertia. F is the applied longitudinal force and the following terms represent the rolling resistance, the longitudinal contribution of the gravity force and the aerodynamic drag force, respectively. Regarding the aerodynamic effect of the platoon configuration, Φ represents the air drag reduction factor that regulates the contribution of the aerodynamic drag as a function of the current distance to the preceding vehicle d. With small following distances $1 > \Phi > 0$ and when traveling solo $\Phi = 1$. Further details about this model can be found in Wang and Rakha (2017); Turri *et al.* (2017).

However, the dynamics in Eq. 1 is not suited for the present experiment. As the vehicle is static in the room, there is no significant air flow around the vehicle and the rolling resistance is based entirely on different phenomena. For that reason, a experimental identification method is used to obtain the transfer function of the model. This approach is typically presented in introductory control courses and is also used to identify the longitudinal dynamics of full-scale vehicles in real-world platoon experiments (Ploeg *et al.*, 2011). In this case, the longitudinal dynamics is reduced to a linear first order system as

$$\tau\dot{v}(t) + v(t) = K_g\, u(t), \tag{2}$$

where $v(t)$ is the longitudinal speed and $u(t)$ is the DC motor input. Thereby, the dynamics of the longitudinal position is written as second order transfer function

$$P(s) = \frac{X(s)}{U(s)} = \frac{K_g}{s\,(\tau\, s + 1)}. \tag{3}$$

Particularly, on the treadmill, the vehicle model has to incorporate the speed of the conveying belt $v_c(t)$. Therefore, the resulting equation of motion become

$$\tau\dot{v}(t) + (v(t) - v_c(t)) = K_g u(t), \tag{4}$$

where m is the total mass and c is a viscous friction coefficient. The vehicle-following scenario is illustrated in Fig. 3. Even with a single vehicle, the following task can be executed because the displacement of the conveying belt represents the behavior of a hypothetical leading vehicle.

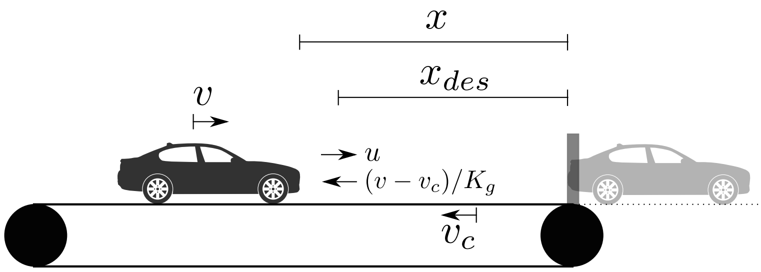

Figure 3. Representation of the vehicle on a treadmill and the front barrier as the hypothetical leading vehicle.

5. LONGITUDINAL CONTROLLER

Two controllers are necessary to keep the vehicle safely in a platoon. As seen in Fig. 3, the longitudinal controller is designed to keep the desired distance x_{des} between the controlled vehicle and the preceding vehicle. In this paper, a proportional controller is used with a feedforward compensation. A simple lateral controller is implemented considering the lateral position and yaw angle to keep the vehicle on track. The design and performance evaluation of the lateral controller is out of the scope of this paper.

The longitudinal control diagram is presented in Fig. 4, where the dynamics of the vehicle is given by Eq. 3. The feedforward term compensate the effect of the moving conveying belt detailed in equation 4. Distance x is measured using the frontal ultrasonic sensor and the control effort is realized through the four DC motors (one at each wheel) simultaneously.

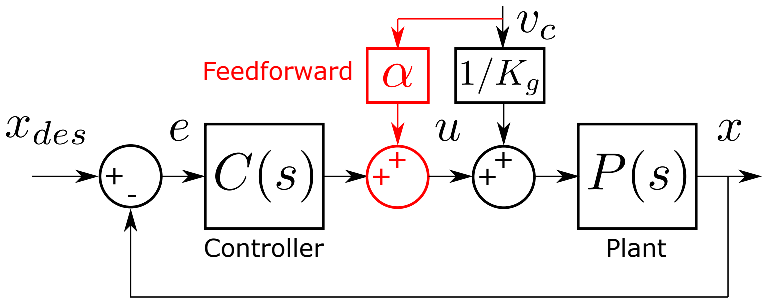

Figure 4. Control diagram of the vehicle-following scenario.

Using a simple proportional controller, the closed-loop dynamics is given by the second order transfer function

$$T_P(s) = \frac{X(s)}{X_{des}(s)} = \frac{K_p K_g}{\tau s^2 + s + K_p K_g}. \tag{5}$$

6. EXPERIMENTS

The main experiments are presented and discussed in this section. A demonstration video of the experiments can be found at https://youtu.be/ss-UzZKDp_4. The Arduino source codes and additional Matlab scripts are available at https://github.com/andresmendes/vehicle-prototype.

All the following experiments used the USB serial communication to acquire the data from the sensors connected to the Arduino board.

6.1 System identification

In this section, the system dynamics is identified, i.e., the values of the gain constant K_g and time constant τ from Eq. 3 are estimated. The identification procedure uses the least square method based on the speed signal of the vehicle in an open-loop step response experiment. However, the speed signal is not directly measured. Instead, the position of the vehicle is acquired using the frontal ultrasonic sensor. The speed data is obtained through numerical differentiation of the position signal. The identification algorithm is developed in Matlab using the optimization toolbox Tomlab.

Figure 5 illustrates the results of the identification procedure. At the bottom, the step input signal is plotted. It starts at t=0.18 s with amplitude u=80 and is simultaneously applied to the four DC motors. At the top, the displacement of the vehicle is presented and, after the numerical differentiation, the speed data is plotted below. Although significant noise is present in the speed signal, the fitted model is consistent with the input and displacement values.

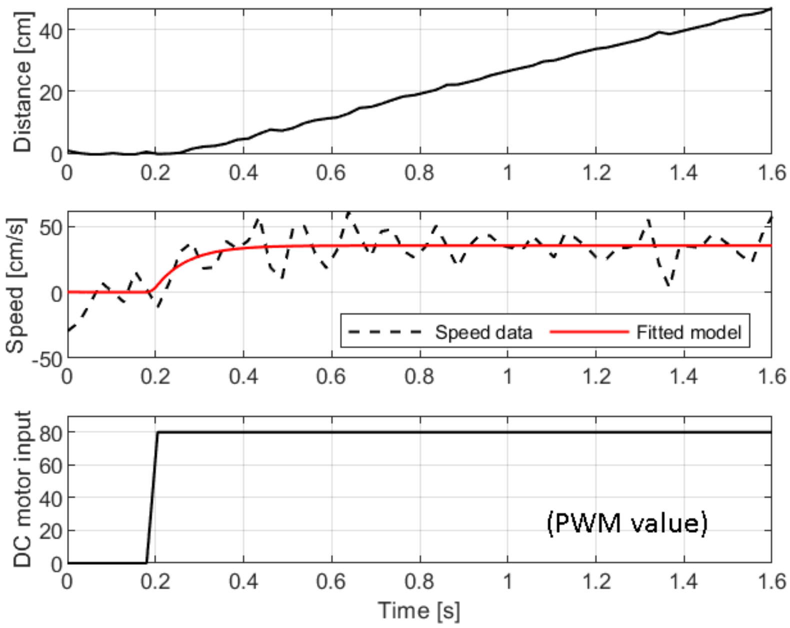

Figure 5. Step response of the open-loop system. The measured displacement is acquired by the frontal ultrasonic sensor and the speed data is obtained through numerical differentiation of the displacement signal.

The estimated values of the parameters are τ=0.07 s and K_g=0.44. Thus, the open-loop poles of the system 3 are located at s_1=0 and s_2=-13.8.

The specific identification procedure described above is not typically covered in introductory control courses. However, this experiment may support class discussions and facilitate the understanding of students about other identification methods, dynamic systems and open-loop response.

6.2 Tracking performance

In this section, we analyze the response of the closed-loop system to a step change of the reference input. To better understand the closed-loop behavior of the system, the root locus diagram of the second order plant model is presented in Fig. 6. Increasing the gain of the system above K=7.8 (Breakaway point: $s_{1,2}$=-6.9), the poles of the closed-loop system have a nonzero imaginary component. Moreover, the system is stable for any positive value of the control gain. In this experiment, the control gain is K_p=10, thus, as indicated in Fig. 6, some overshoot is expected. Figure 7 illustrates the performance of the longitudinal controller for a series of step inputs showing the separation distance (above) and the control effort (below) signals. The speed of the treadmill is kept constant while the desired distance is changed.

At the beginning, the desired distance is x_{des}=30 cm. After 4 seconds, the desired distance is reduced to 25 cm. In this case, we can see an increase of the control input to reduce the gap between the vehicle and the front end of the treadmill. Subsequent step changes are applied varying the desired distance between 25 and 35 cm. At the end, the value of the desired distance returns to x_{des}=30 cm. It can be seen that the control effort and the overshoot are proportional to the step size as expected. Note that the range of the control input value is limited between 0 and 255 by the pulse width modulation (PWM) of the analog output of the Arduino board.

In this experiment, the teacher can illustrate the fundamental difference between open-loop and closed-loop systems. Moreover, reference tracking and control design specifications can be addressed using real-time measurements as seen in Fig. 7.

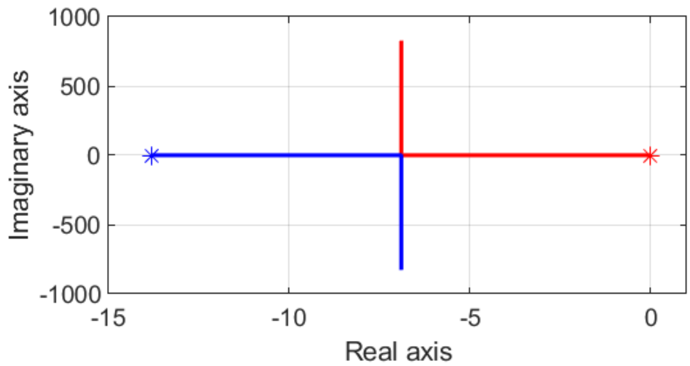

Figure 6. Root locus diagram of the second order plant model. Breakaway point: $s_{1,2}$=-6.9 at K=7.8.

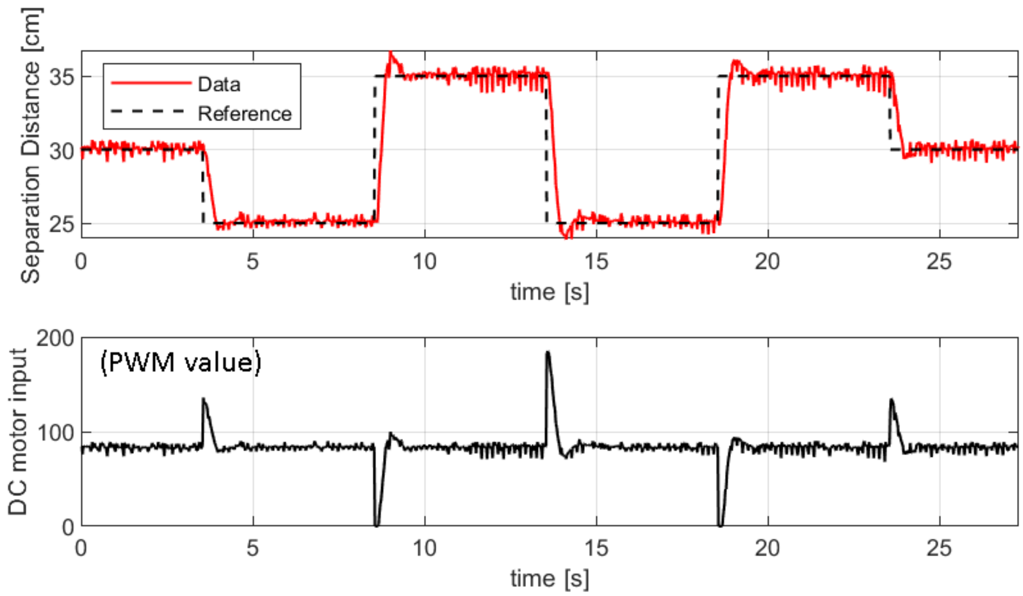

Figure 7. Step response of the closed-loop system with a proportional controller and a feedforward compensation. Above, the measured data x and the reference signal x_{des} are plotted and, below, the control effort is plotted.

6.3 Disturbance rejection

To verify the ability of the controller to reject disturbances, the speed of the conveying belt is, once again, kept constant while an object is suddenly placed in between the front barrier and the vehicle. The readings of the frontal ultrasonic sensor are abruptly changed and the controller has to compensate this effect by adjusting the separation distance to match the desired value. Figure 8 illustrates the separation distance (above) and the control effort (below) over time. Since the object is placed manually in front of the vehicle, there is no exact information about the position and insertion time. However, the peak values from the signals in Fig. 8 indicate the insertion and removal of the object from the measurable range of the ultrasonic sensor.

At the beginning, the vehicle is at 30 cm from the preceding vehicle and, at t ≈0.4 s, the object is suddenly placed in front of the vehicle reducing the measured separation distance. The control effort drops rapidly to zero and then increases while matching the desired distance. The object is kept still in front of the vehicle up to t ≈1.8 s, when it is suddenly removed. Now, the measured distance is increased to x=38 cm and the control effort increases to u=165 to reject this disturbance. This sequence is repeated another two times and the results can also be seen in figure 8.

This experiment addresses controller disturbance rejection capability and supplement the study related to reference tracking by offering the students a more informal hands on interaction with the platform. The students have the opportunity to handle the object and explore the system by changing the measured separation distance and visualizing the following behavior. Alternatively, the speed of the conveying belt could be changed for additional discussion on disturbance rejection.

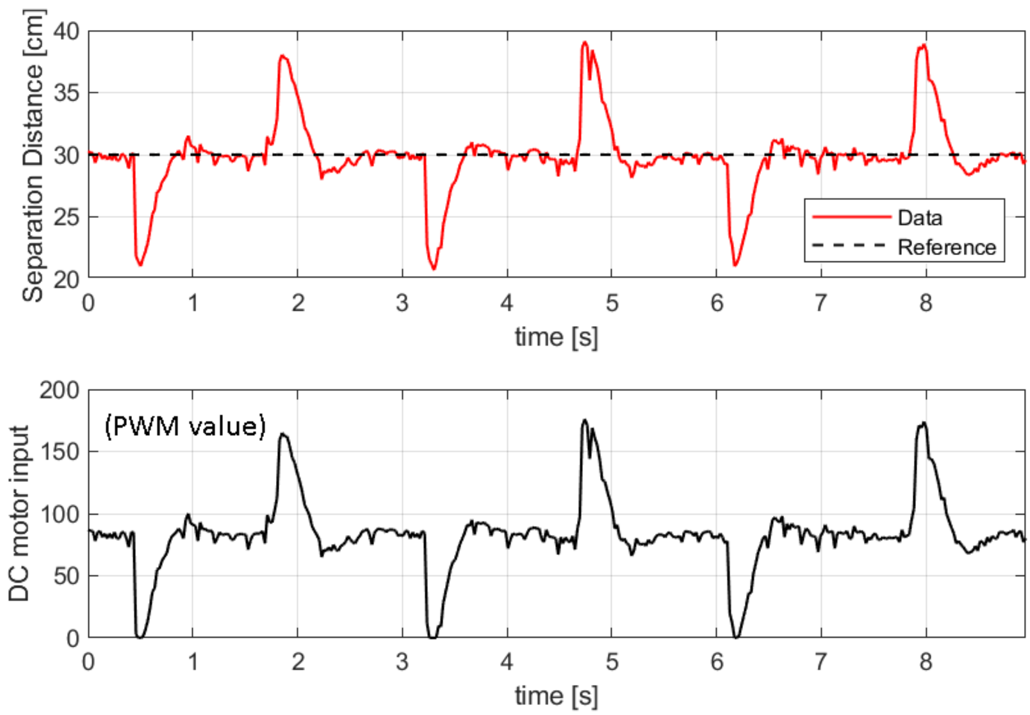

Figure 8. Disturbance rejection of the closed-loop system with a proportional controller and a feedforward compensation. Above, the measured data x is plotted and, below, the control effort is plotted.

7. SUGGESTIONS FOR IMPROVEMENTS

This paper presents the first version of a testing platform for vehicle-following control demonstration. The experiments described here can be implemented in an introductory control course to increase students interest and engagement. Although designed for a control course, this vehicle platform can also be used to address other engineering topics such as system dynamics, signal processing, programming and simulation. Moreover, this platform can be used in research related activities in the field of automated vehicle systems.

Future improvements include the replacement of the Arduino MEGA with Arduino Uno for cost reduction. Data logger shield and onboard batteries should be used to allow standalone experiments without communication and external power supply connections. Finally, the effectiveness of the platform as an educational tool should be evaluated using surveys and pre/post quizzes.

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